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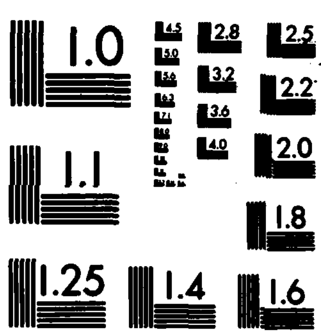

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A comprehensive model of soil-water dynamics, a "wetting front" model, was developed and tested. The model represents a variety of flow processes including infiltration, redistribution, drainage and evaporation. The accuracy of the model was tested by comparison with results from a finite difference solution of the Richards equation and was found to be a reasonable representation. The model was used to investigate the extent

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to which observed spatial variability in soil moisture may be due to soil heterogeneity. Results suggest that in excess of 50% of observed variance in soil moisture may be attributable to soil heterogeneity. The relationships among soil hydraulic parameters, the specification of which is necessary for any physically-based model including the wetting-front model, and soil physical characteristics were investigated using multivariate statistical methods. Statistical properties of the parameters in each soil textural class have been tabulated.

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PROBLEM STATEMENT

Many fundamental environmental problems are related to the movement of water through soil. For example, flood discharges are strongly affected by infiltration rates, drought damages result from excessive evapotranspirational losses from soil, and the transport of potentially harmful chemicals may be associated with the flux of soil water. Despite the significance of soil hydrology to these and other problems, the techniques used to model field-scale, soil-water systems are largely empirical. The usual approach is to route soil moisture from compartment to compartment in a "black box" fashion. Empirical approaches are attractive because of their simplicity. However, they share problems of uncertain applicability beyond specifically tested situations and require historical data (often unavailable) for calibration, because parameters in such models are, in general, impossible to relate directly to physical characteristics of the soil.

The alternative approach, based on soil physics, requires the solution of the differential equation of Richards (1931) which itself is a combination of Darcy's law and continuity. Because solutions to the equation are complex and because soil-water movement is mainly vertical, soil physicists have concentrated on the one-dimensional form of the Richards equation. Even with this simplification, the equation has rarely been used to model actual field conditions for several reasons.

First, solutions of general interest require numerical models that are very costly to use for lengthy simulations. The high cost results from the small time and space increments that must be used due to the nonlinearity of the hydraulic properties of soil. Although some numerical errors may be tolerated in field applications, there are no clear guidelines to fixing these increments. Second, due to the complexity of the numerical solutions, modelers with experience and advanced mathematical training are needed to implement them. Third, the data requirements for most field-scale problems are immense. The two critical functions, the soil moisture characteristic curve and the moisture-dependent hydraulic conductivity, are difficult to measure. Moreover, soils are notoriously heterogeneous, often requiring extensive sampling programs. For these reasons the application of the Richards equation is usually unjustified despite its potential accuracy due to its rigorous physical basis.

Clearly, a model that is grounded in soil moisture theory but computationally more efficient than conventional numerical models could be a very useful tool. If the uncertainties due to the simplifying assumptions are small, then a simplified, efficient model could be advantageous in applications characterized by considerable uncertainty in the soil parameters or the meteorological inputs. In addition, such a model could be advantageous where other processes such as runoff, groundwater flow or chemical transport are of prime importance.

The infiltration model of Green and Ampt (1911) provides a clue for developing a simplified model. In conventional numerical models, the infiltrating water is represented by a series of nodes each having a fixed depth and a variable moisture content. In contrast, the Green-Ampt model depicts a moisture discontinuity, termed the wetting front, which descends down into the profile. This wetting front can be construed as a single node having a variable depth and a fixed moisture content equal to saturation. Long considered to be empirical, the Green-Ampt equation was derived by Neuman (1976) by integrating Darcy's law and by assuming simplified distributions for the flux and the hydraulic conductivity behind the wetting front. This same approach can be generalized to other flow processes besides infiltration by incorporating an integrated version of the continuity equation and thereby calculating an average soil moisture content behind the wetting front. For most flow processes, this moisture content is allowed to change with time so that each wetting front in such a model is characterized by both a variable depth and a variable moisture content.

Using Neuman's derivation (1976) of the Green-Ampt equation as a point of departure, the primary goal of the research reported herein was to build a comprehensive model of soil-water dynamics. The model portrays the moisture profile as a series of rectangular blocks each typified by an average moisture content and each bounded above and below by wetting fronts, hence the name wetting-front (WF) model. The overall model is a merger of several submodels, representing different flow processes (e.g., infiltration, redistribution, drainage). Each submodel is developed and tested independently, and each is comprised of a set of equations for the flux and for the moisture change within the appropriate segment of the moisture profile. The model is briefly described by Clapp et al. 1983. The details of the derivation of the model and of the extensive tests to which it has been subjected are reported in Clapp (1982).

The model was used to investigate the spatial variability of soil moisture due to soil heterogeneity by Clapp et al. (1983). Applying a probabilistic simulation technique with input data appropriate to watersheds R-5 and R-7 at Chickasha, Oklahoma, they found that variability in soil moisture due to soil heterogeneity remains relatively constant through time.

The WF model, as a physically-based model, requires that the hydraulic parameters of the soil be specified. To make the model generally applicable, predictive relationships describing the hydraulic parameter distributions must be developed based on the common descriptors of the physical properties of soils (i.e., texture, structure, particle size distribution, etc.). Cosby et al. (1984) used multivariate statistical techniques with a large data set to determine the appropriateness of such predictive relationships.

SUMMARY OF IMPORTANT RESULTS

The publication of the Richards equation (Richards, 1931) marked the beginning of modern soil physics with its emphasis on the mathematical description of soil water movement. Since that event the soil physics literature has been filled with the results from soil-column studies, and these results indicate that we are very knowledgeable about the dynamics of soil water in ideal soils. To date, the number of field studies where basic physical principles have been investigated are far less numerous, and the results generally indicate that under field conditions soil water dynamics are very complex due to the interaction of many factors such as natural heterogeneity and non-Darcian flow during infiltration into macropores.

The underlying idea behind our research is that soil physics gives us a few basic conceptualizations of the fundamental hydrologic processes within the soil and that these conceptualizations can be embodied in simple analytic equations. Furthermore, these equations can be linked together using a functional approximation to the soil moisture profile in order to form a simple model that is at once both justifiable in terms of soil physics and applicable to a variety of hydrologic problems.

Based on a number of simplifying assumptions (Clapp, 1982), the wetting front model computes instantaneous rates for and cumulative depths of infiltration, evaporation and drainage. Infiltration estimates are expected to be as accurate as those generated by the direct application of the Green-Ampt model itself. The WF approximations introduce no substantial sources of error to the calculation of infiltration. In test simulations comparing model solutions to those generated using a conventional finite differencing scheme, positive errors (overestimations) for infiltration from individual storms averaged about 5%. These model errors are attributed to errors in the assumed distribution of hydraulic conductivity inherent in the Green-Ampt model. Negative errors result from the model's simplified, rectangular moisture profiles that underestimate the near-surface moisture deficit after prolonged periods of evaporation. In the test simulations, these errors ranged to -25% although the absolute errors were small (<.4 cm); cases where the initial moisture content is nonuniform are problematic to any analytical infiltration model.

After water infiltrates into the soil, it redistributes with the profile. Quantifying the interaction between redistribution and evaporation is one of the most important contributions to soil hydrology of this study. The key component is the evaporation submodel that computes the soil's instantaneous evaporability, a rate analogous to infiltrability in the Mein-Larson/Green-Ampt model. The expression for evaporability is derived from a concentration-dependent, analytical diffusion equation, and it depends on the mean weighted diffusivity. In this study, explicit expressions for this parameter were developed. In the process, the air-dry surface assumption, required by the original diffusion equation, was shown to be robust, i.e., the surface moisture content can range to .06 cm^3 cm^{-3} for a coarse-textured soil and to .12 cm^3 cm^{-3} for a fine-textured one without significant error to the calculated evaporability.

However, evaporability is very sensitive to the moisture content at depth. Because redistribution and internal drainage are continuous processes, there is no apparent way to designate a single value for the moisture content at depth in order to characterize soil water evaporation. The only recourse is to link evaporation and redistribution through the instantaneous value of the moisture content at depth, as is done in the evaporation submodel. Unfortunately, in the formulation of the submodel the assumption of a steady moisture content at depth, i.e., the field capacity assumption, is not altogether eliminated. As a result, there can be a bias towards underestimation of the evaporation with the magnitude of the error increasing with increases in the prior infiltration and increasing for finer-textured soils. In one model application, after 10 cm of infiltration into a clay loam, the error in the computed evaporation was -22% after 16 days. Because conditions favored underestimation in this case, errors in evaporation are generally expected to be smaller.

In test simulations, the WF model generated infiltrations and evaporations for individual storms and interstorm periods, respectively, that were usually within 10% of agreement with FD solutions. The model also estimated the cumulative components of the water budget within 7%. Thus, the model is judged to be applicable to homogenous soil systems where the uncertainty is of the order of 10%.

The model's most practical advantage over conventional numerical techniques is its computational efficiency. In the test simulations, the basic model required as little as .03 of the computer time required of the FD model.

A modified version of the WF model accounts for some of the basic hydrologic effects of soil layering. Although this model does not include lateral subsurface drainage, it estimates infiltration fairly well (relative to FD solutions) using the layered-soil version of the Green-Ampt model. However, it can simulate an evaporation that is significantly biased because the evaporability is calculated from the parameters of the surface layer only. In light of the 27% underestimation of total evaporation in one of the comparative simulations, the modified model is judged to give at least a qualitative estimate of the water budget for layered soils, and this may be sufficient for some hydrologic problems.

The WF model is limited to bare-surfaced and homogenous soils; but in the realm of soil physics, where applicable, the model is an appropriate alternative because it is physically based and accurate as compared to a conventional finite difference model.

When one moves from the conceptualizations of soil physics to the realities of hydrology and watershed management, the WF model can serve as a valuable tool. It is useful because it is computationally efficient and because it provides a potential for accuracy not expected of conventional "black box" models that treat soil water processes independently. This last point leads to the exciting prospect of relating the bulk parameters obtainable from direct field measurements of infiltration to other bulk parameters in the expressions for evaporation via basic functions for soil hydraulic properties, and such a capability would be a major advance in hydrology.

The results of Monte-Carlo simulation to estimate the effects of soil heterogeneity on the variability of measured soil moisture (Clapp et al., 1983) show that there is relatively constant variability during a storm when there is uniform saturation behind a wetting front, followed by an increase shortly thereafter due to redistribution, followed by a slowly decreasing variability. However, for the most part, the variability due to soil heterogeneity is constant through time. Averaging observed and calculated variability indicates that 75% of the observed standard deviation (or 56% of the variance) can be attributed to soil heterogeneity. Our results show that by ascribing all of the uncertainty in a soil system to scaled differences in the soil matrix, one may be limiting the mathematical simulator to a certain pattern in the variability in the computed moisture content. These results also show that soil heterogeneity as represented through scaling theory can account for much of the observed variability in near-surface soil moisture. This is particularly striking because one can identify so many other possible sources of variability in the plant-soil system.

In analyzing the data of Holtan et al. (1968) to determine whether soil hydraulic properties could be predicted on the basis of soil physical properties, we found that, of all the physical soil descriptors available, variability in texture was most closely related to variability in the soil moisture parameters (Cosby et al., 1984). This result has led to tabulation of the statistical properties of the parameters in each textural class, a useful step in understanding the variability of the parameters. We have been able to extend these results in two ways. The discriminant analyses suggest an intuitive qualitative explanation for the observed relationship between parameter distribution and soil textural characteristics. The regression analyses provide a quantitative means of specifying the expected statistical properties of the parameters for a given soil type.

Soil textural classes are determined uniquely by a combination of three variables, the percent sand, silt and clay content of the soil. In this system, there are in reality only two independent variables and these variables define a planar space such that each textural class occupies a unique region of the space. The discriminant analyses on the hydraulic parameters resulted in two important functions, each of which produces a single variable that is a linear combination of the hydraulic parameters. These two functions are orthogonal and can also be taken to define a planar space which may be divided into unique regions. The striking result of this analysis was that the two spaces showed a definite one-to-one mapping. That is, for a "typical" soil of a given textural class, the sand-silt-clay space is isomorphic with the hydraulic parameter space. Since it is intuitively reasonable that the hydraulic characteristics of a soil are determined by the particle size distribution of the soil, it would also seem reasonable that any set of hydraulic parameters that can define a planar space which provides the same discrimination between soil samples as a planar space based on the particle size distribution would be the minimum set of hydraulic parameters necessary to characterize the hydraulic behavior of the soil (at least to the same degree of resolution as that provided by the particle sizes.) Thus we can infer that the parameters studied in our work provide a nearly complete description of the hydraulic characteristics of soils given the information available.

Of more practical importance are the results of the regression analyses. The fact that the variances as well as the means of the hydraulic parameters are functions of soil textural class, has not been reported before. That there is more inherent variability in the parameters in certain classes is perhaps not surprising. That the variability can be explained so simply as a univariate function of the sand, silt or clay content is surprising. The large reductions in F ratios from the analysis of variance suggest that the regression equations are very robust since they can remove so much of the pattern in the parameter distributions. It must be emphasized that the patterns extracted in this analysis, while significant, are still embedded in a large amount of noise. The parameter variances for each textural class are not small relative to the means and the patterns we observed may have been detectable only because of the large data set available for analysis. For any particular soil sample or small group of samples, the relationships described above may be obscured.

Attempts to model the observed spatial variability of soil moisture are commonly based on an assumed variance in the moisture parameters for a given soil type. Reliable estimates of the size of the variance to be used (or for that matter of the parameter means) have been lacking. Furthermore, the manner in which these means and variances might change in heterogeneous systems of mixed soil types has not been investigated either. The results presented here, having been derived from a large, diverse set of soil samples, should be indicative of the true pattern of variability in the hydraulic parameters. The use of these parameter class means and standard deviations for a known soil textural type may improve the predictions from stochastic models utilizing a homogenous soil. The use of the regression equations for the parameter means and standard deviations should add increased sophistication to models which incorporate distinct layers of different soil types. Because the regressions are continuous in the variables, it may be possible to construct models that are based on continuous spatial variation in physical properties.

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